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PERFORMANCE TESTS AND ANALYSES ON A 7 FOOT HYDROSPHERE MODEL.(U)
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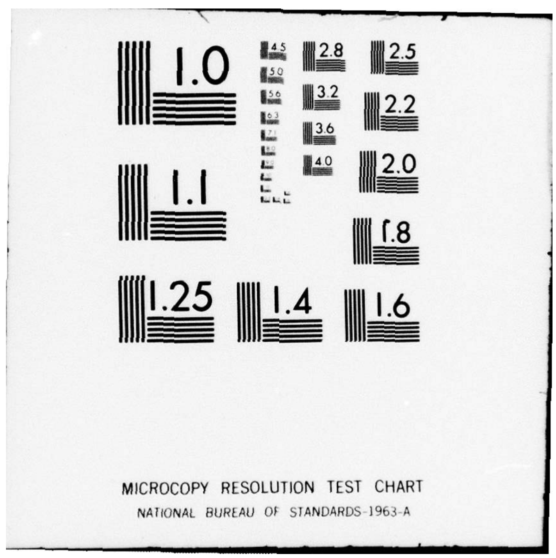
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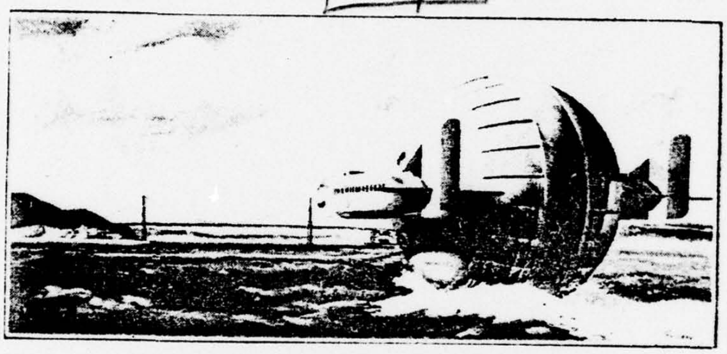

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TABLE OF CONTENTS

RE: Appendix A
The pages that have the printing cut off are not important per Mr. D. Smith, DTNSRDC

I. BACKGROUND INFORMATION

The Hydrosphere is a unique vehicle in that it is both a vehicle and a propulsion system in a single form; that is, the sphere is the vehicle and the rotation of the sphere provides the propulsion. Some years ago, this concept was proved by Dr. Alex Dandini, who is currently with the University of Nevada, Reno. Dr. Dandini designed, fabricated, and successfully operated a ten foot diameter sphere. This sphere had small air propellers on each side for directional control and used a gyroscope for lateral stability. Power for the sphere was provided by a 120 hp Studebaker engine driving six automobile wheels which ran on tracks on the shell's interior. The propelling torque was provided by the weight of the engine being forward of the center of buoyancy. It was noted that under static conditions the depth of the submergence was approximately 20% of the sphere's diameter. The exterior was circled by two parallel keel bands, and extending outward from each keel band were 24 propulsion vanes tapering in height from the height of the keel band to about one inch at a distance of three feet outward.

Dr. Dandini operated the Hydrosphere in various sea conditions in and around the San Francisco Bay Area. He reported speeds up to 34 mph and observed high propulsion efficiency (low slip), amphibious operation, and excellent stability. The Hydrosphere was destroyed in a fire before more advanced development could be undertaken. Many years then elapsed before the U.S. Navy became interested in unique concepts for rollercraft and propulsors which operate through air-water interfaces. A meeting was held at the Naval Ship Research and Development Center, Anapolis (NSRDC/A), March, 1973, wherein various new concepts were discussed. Among these was the Hydrosphere as presented by Mr. D.F. Smith (NSRDC/A). It was

decided that basic experiments should be conducted with the Hydrosphere concept to determine such factors as:

- Size and scaling effects in order to justify extrapolation of model results to full size systems.
- Vane spacing and configuration in order to optimize system performance.
- Characterize the Hydrosphere using the concept of "propulsion efficiency."

A study was conducted at the Desert Research Institute (DRI), University of Nevada System, during the period July 1, 1973 to June 30, 1974. The study involved the design, fabrication, and testing of a three foot diameter Hydrosphere model. Various tests were conducted by the DRI to determine the effects of various vane spacings and configurations, the amount of slip, and qualitative information concerning power, stability and smoothness of performance. Some useful data has resulted from these previous studies, namely, proof of concept, slip data as a function of sphere diameter, vane design information, and qualitative data in the form of movie film. It was concluded that a larger diameter sphere should be designed, fabricated, and tested to determine scaling effects as a function of diameter. A seven foot diameter sphere was chosen primarily due to the availability of a mold for fabrication of the sphere using fiberglass.

Scientific Engineering Systems, Inc. of Reno, Nevada was awarded a subcontract by the University of Nevada, Reno to provide engineering services for the management, design, fabrication, and testing phases of the seven foot Hydrosphere program. The actual cost of materials, sphere fabrication, machine shop work, and instrumentation was subcontracted on a direct cost basis. The university of Nevada provided special facilities, instrumentation, and limited support whenever possible.

The seven foot Hydrosphere was successfully designed, fabricated and subjected to initial testing. There have been several reports prepared and submitted to NSRDC/Annapolis during these past two years, namely:

Interim Report I - This report provided background information, theoretical discussions, preliminary design information including structural, power plant considerations, control systems, weight estimates, and experimental procedures.

Interim Report II - This report provided a detailed summary of the various design options considered, the selection of a design method, a design report including structural, control systems, propulsion vane design, engine components, and proposed data acquisition methods.

Interim Report III - This report provided a submission summarizing fabrication procedures, problems encountered, and techniques employed leading to the final assembly of the seven foot Hydrosphere.

Final Report - Part I - This report included a brief outline of each of the above noted Interim Reports, as well as detailed discussions covering the periods of testing. The initial data gathered was presented along with preliminary conclusions and recommendations.

Final Report - Part II - This report included a discussion about throttle control system changes that provided improved steady state performance. Additional testing was accomplished and the results presented in this report. A more detailed discussion of the theoretical aspects of dynamic similarity was presented with specific applications being made to the Hydrosphere concept. A review of 3 ft data was made and the results were also summarized in this report. Conclusions and recommendations for future work were included.

The University of Nevada along with Scientific Engineering Systems, Inc. have been able to complete a considerable amount of design and

fabrication activity and still carry out a significant amount of work in a fairly short time on a modest budget.

The Hydrosphere model was operated satisfactorily and in the opinion of an outside consultant, Dr. Allen Acosta, "...the data obtained are meaningful and represent real physical events for the operation of the Hydrosphere." The basic problem was that there was not sufficient funding available to gather the extensive data required to provide a technical base for the evaluation of the Hydrosphere propulsion concept.

A major justification for additional testing centered around the fact that the University of Nevada had developed an operating model of the Hydrosphere and the performance data taken on this model indicated significant potential for some naval applications. The data were not, however, sufficient to provide an explanation for a significant scattering of data points. An additional contract was let to the Engineering Research and Development Center (ERDC), University of Nevada, to develop and conduct a test program, utilizing the seven foot model for the purpose of generating supplemental data necessary to resolve this apparent disparity and to establish the feasibility of this concept for a variety of potential Navy operational applications.

A subcontract was let to Scientific Engineering Systems to aid the ERDC in developing, conducting and reporting on this additional test program. A suitable test plan was prepared and submitted to the Navy for approval. The basic approved test plan and subsequent field trials are described in the next sections of this report. Also included are conclusions and recommendations for future work.

II. ACQUISITION, PROCESSING AND TABULATION OF THE ADDITIONAL TEST DATA

A number of test runs were made at two lakes near Reno, Nevada, i.e., Boca Reservoir and Lake Tahoe. The course was set up in each case parallel to the shoreline. The length of the course for the additional testing program was 150 feet. A 16 mm camera was used to record the test runs and a stopwatch was used to provide run times. A summary of the data gathered is shown in Appendix A. A record of the films taken is shown in Appendix B. Runs 1 through 30 represent the data previously reported in Final Report, Part II. The additional testing data were recorded using run numbers 31 through 205.

The data were gathered and categorized according to the following general experimental procedures: (See Appendix A)

1. Self propelled, free running mode

   Data were gathered while operating the Hydrosphere in a self-propelled, free running mode over the 150' measured course. The data runs under this category are 31-91 and 120-162 (inclusive).

2. Self propelled and towing mode (Figure 1)

   Data were gathered while operating the Hydrosphere in a self propelled and towing mode over the 150' measured course. The data runs under this category are 92-119 (inclusive).

3. Locked sphere and towing mode

   The Hydrosphere was "locked" so that it would not rotate. The chase boat provided a tow force and pulled the Hydrosphere over the 150' measured course. The data runs under this category are 163-174 (inclusive).

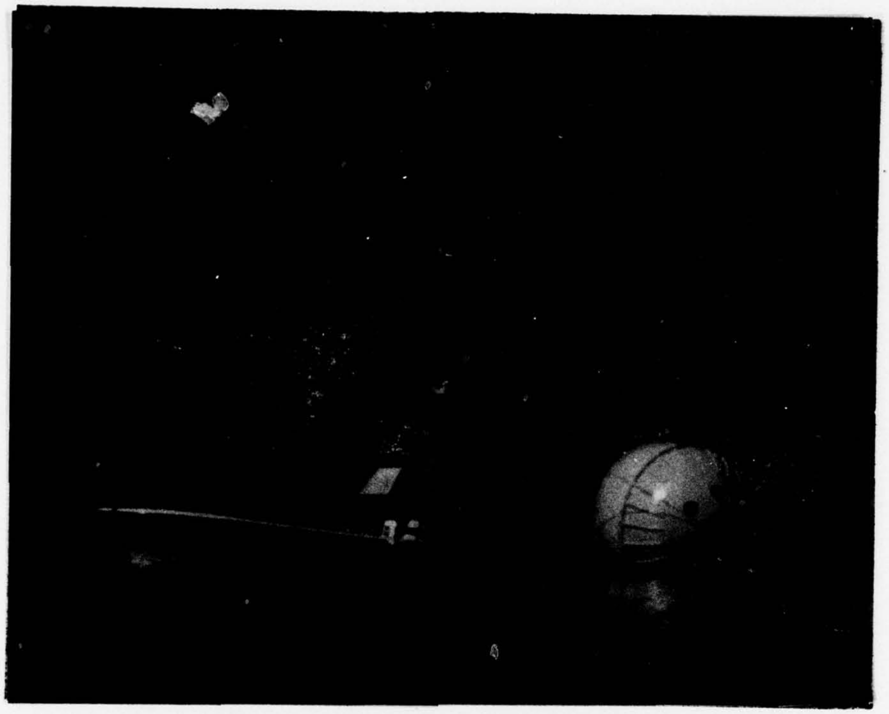


Figure (1) - Photograph showing the Hydrosphere towing setup.

4. Free rolling sphere and towing mode

The Hydrosphere was allowed to roll freely by removal of the drive chains. The chase boat provided a tow force and pulled the rolling Hydrosphere over the 150' measured course. The data runs under this category are 175-181 (inclusive).

5. Reverse free rolling and towing mode

The Hydrosphere was allowed to roll freely by removal of the drive chains. The Hydrosphere was pulled "backwards" in order to determine whether or not there would be a noticeable difference due to vane effects. The data runs under this category are 182-186 (inclusive).

6. Underwater films

The Hydrosphere was operated in several self propelled, free running and towing modes while underwater films were taken. The data runs under this category are 187-205 (inclusive).

A special underwater camera system, Figure 2 , was fabricated in order to accomplish the underwater filming. A diver was placed in approximately 15-20 ft of water directly under the Hydrosphere test course. Excellent films resulted due primarily to the excellent clarity of the water in Lake Tahoe. The films are quite useful for studying the sphere-water interface under dynamic conditions.

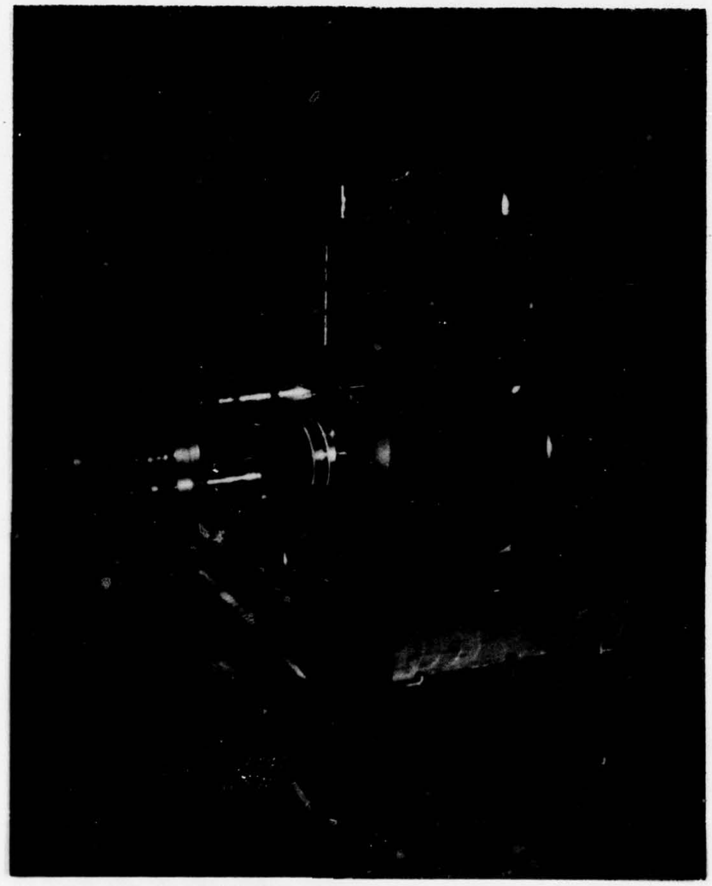


Figure (2) - Underwater camera used for filming of the Hydrosphere at Lake Tahoe.

A computer program was written to aid in processing the data obtained from the many data runs. This program is included as Appendix C. The general program inputs and outputs are described below:

Program inputs

RUN = Run number

REV = Number of revolutions over the 150' course

TIME = Run time over the 150' course (sec)

THETA = Torque angle of the engine system referenced to equilibrium (degrees)

FTOWR = Towing force by the chase boat (lbf)

THETAR = Towing angle of the tow line (degrees)

Program calculations and outputs

The various equations used to process the data have been discussed in detail in Final Report, Part II. A brief summary of these equations and the corresponding program outputs are described below:

- OMEGA $= \frac{\text{\# of revolutions over the 150' course}}{\text{run time over the 150' course}}$

- SLIP $= \left(1 - \frac{R_i}{R_a}\right) 100\ (\%)$

where,

R_i = ideal number of revolutions over the 150' course, i.e., zero slip

$= \frac{150}{\pi D} = \frac{150}{\pi(7)} = 6.8$

and,

R_a = actual measured number of revolutions over the 150' course

- VCLFPS = Centerline velocity $= \frac{150'}{\text{TIME}}$ (ft/sec)

- SPHHP = Power developed by the Hydrosphere

  = 7.48* OMEGA * Sin (THETA)

- TOWHP = Towing power applied to the Hydrosphere by the boat (lbf)

$$= \frac{150 * FTOWR * Cos\ (THETAR)}{550 * TIME}\ (hp)$$

- TOTHP = Total horsepower applied by the Hydrosphere and the tow boat

  = SPHHP + TOWHP

- CD = Effective drag coefficient

$$= \frac{120 * TOTHP}{(VCLFPS)^3}$$

- FR = Froude number

$$= \frac{VCLFPS}{(gD)^{\frac{1}{2}}} = \frac{VCLFPS}{15.01}$$

Also an "effective" drag-lift ratio, η_t, was calculated where

$$\eta_t = \frac{550P}{WV}$$

and,

P = total power applied to the Hydrosphere (hp)

W = total weight of the Hydrosphere (lbs)

V = center line velocity (ft/sec)

The results of these calculations are shown tabulated in Appendix A. The next section of this report will present the various graphical representations that were felt to be best descriptive of the Hydrosphere model performance. Appropriate comments are made concerning each of the data plots.

III. GRAPHICAL PRESENTATION OF THE DATA

A plot was made of the "effective" drag coefficient C_D as a function of Froude number F_r for the Hydrosphere under "locked" sphere and "free rolling" sphere conditions without self propulsion. These points are represented as runs 163-174 (inclusive) for the "locked" sphere and runs 175-181 (inclusive) for the "free rolling" sphere. These data points are shown plotted in Figure 3. These runs were all taken at the same time using the same experimental procedures and equipment, etc.; however, it can be seen that the "free rolling" points appear to be well behaved, while on the other hand, the "locked sphere" points exhibit a more "erratic" behavior. The reason for this is that each of the runs was taken in an opposite direction, so that only every other run is in the same direction. Since there was a light wind blowing at the time, this data would indicate that the rolling sphere performance is much less affected by wind than the locked sphere. It can be seen that in each run the free rolling sphere drag is significantly lower than that for the locked sphere case. The major reason for this is the fact that the rolling sphere is able to pass the bow wave under and around itself thus reducing the effective drag. The data also indicates that above a certain Froude number there is little or no difference between this free rolling and locked sphere operation. This very sharp increase in drag coefficient can also be observed when one considers the relationship between drag - lift ratio and Froude number.

It must be noted that C_D is truly only an "effective" drag coefficient since the data analysis considered here assumes a constant submerged cross sectional area only, i.e.,

$$C_D = \frac{1100\ Pg}{\rho A_s V^3}$$

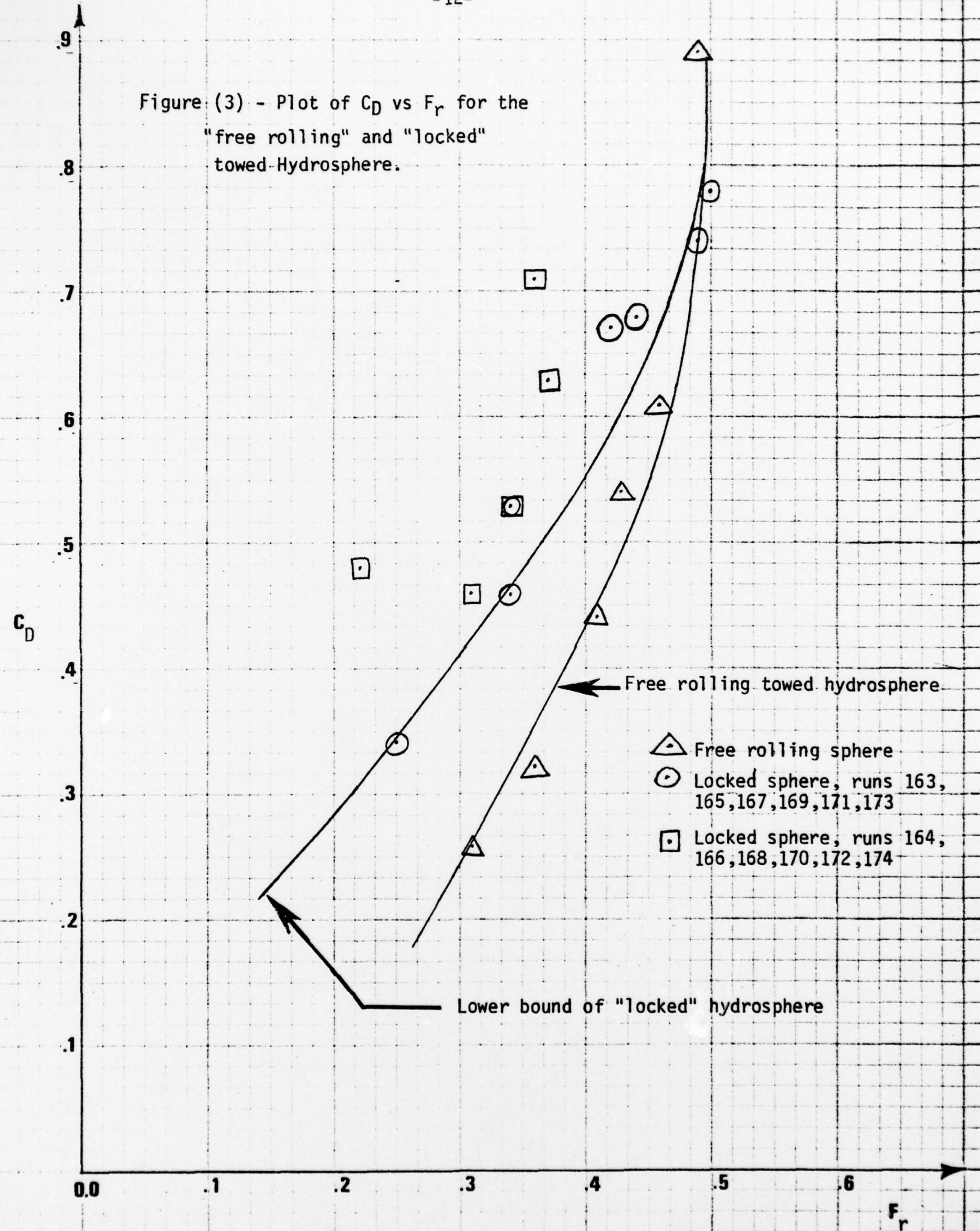


Figure (3) - Plot of C_D vs F_r for the "free rolling" and "locked" towed Hydrosphere.

$$C_D = \frac{120\ P}{V^3} \qquad F_r = \frac{V}{\sqrt{lg}}$$

where,

$A_s \approx 0.8D^2 F^{3/2}\left[\sqrt{1-F} + 0.67\right]$ (the submerged cross sectional area, ft^2)

D = the diameter (ft)

F = fractional part of diameter submerged

P = power (hp)

g = gravitational constant

e = density of the fluid (lbs/ft^3)

V = centerline velocity (ft/sec)

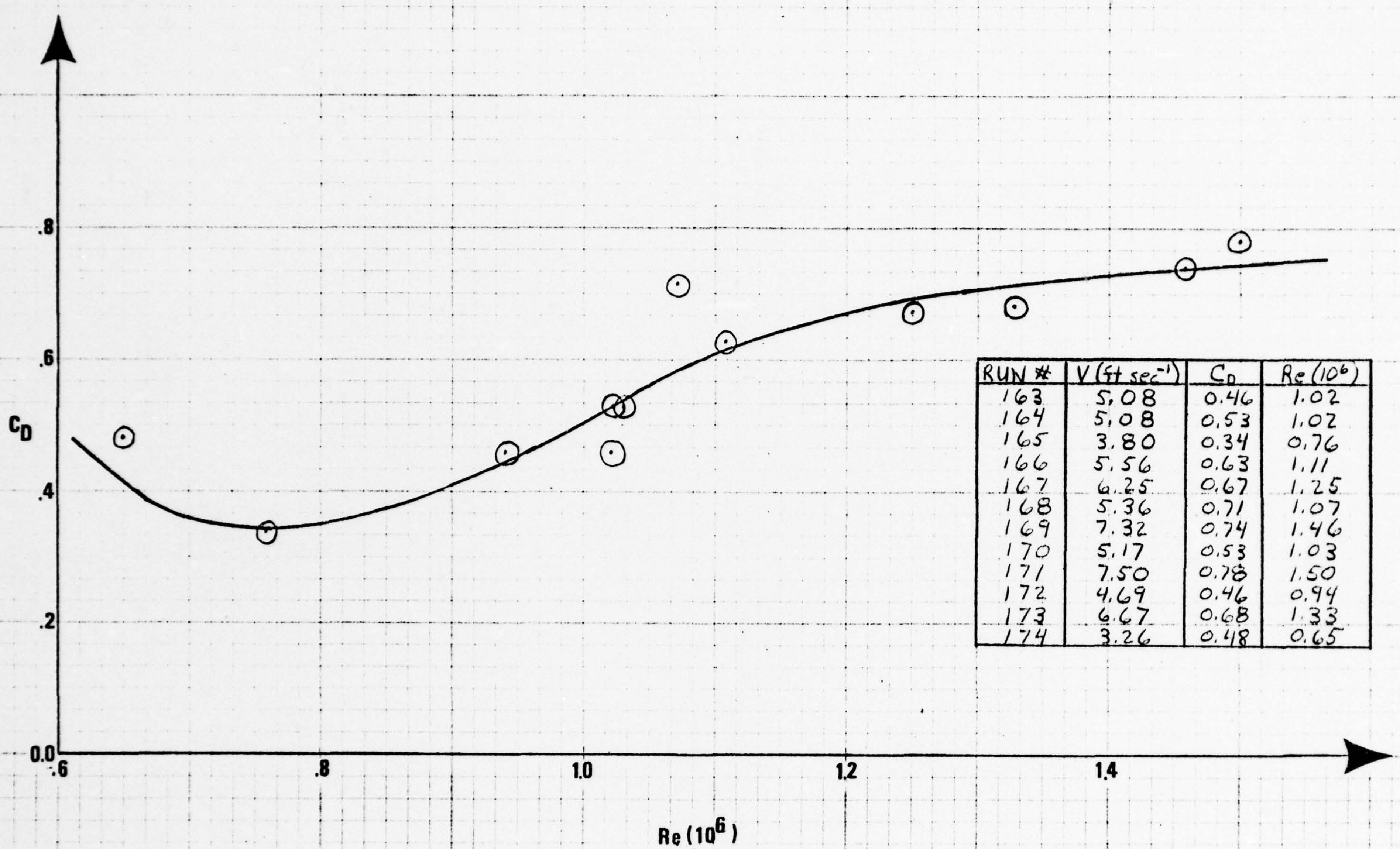
The locked sphere tends to "sit" more firmly down in the water as the towing force is increased. If it were possible to measure this change in submergence the drag coefficient would be calculated to be somewhat lower than that shown. The free rolling sphere does exhibit an excellent steady state behavior with lower drag.

It should be remembered that when flow occurs past a flat surface parallel to it, the fluid exerts a drag force on the surface as a direct result of viscous action. The resultant frictional force in the downstream direction is usually know as the skin friction drag, and the factors on which its magnitude depends are well covered in the literature. In the case of the Hydrosphere, however, relative flow occurs past a surface which is not parallel to the flow and also the surface is allowed to rotate. There are then additional drag forces resulting from pressure differences over the submerged surface area. One must consider, therefore, not only the skin friction drag due to the forces tangential to the surface but also the pressure or form drag forces that are normal to the surface.

In almost all cases in which flow takes place around a solid body of Reynolds numbers greater than about one hundred, the boundary layer separates from the surface towards the rear of the

body. Downstream of the separation position the flow is greatly disturbed by large scale eddies, and this region of eddying motion is usually known as the wake. As a result of the energy dissipated by the highly turbulent motion in the wake the pressure there is reduced and the pressure drag on the body is thus increased. The magnitude of the pressure drag usually depends very much on the size of the wake and this in turn, depends on the position of separation. The locked sphere is not a streamlined body and hence the flow is separated over much of the surface, thus increasing dramatically the pressure drag. The rolling sphere, on the other hand, maintains an attached flow pattern thus providing a reduced wake and a lesser amount of pressure drag. The data plotted in Figure 3 supports this concept.

The flow pattern in the wake of the Hydrosphere depends on the Reynolds Number of the flow. It is useful, therefore, to consider a plot of Reynolds Number versus the effective drag for the Hydrosphere. It is well documented in the literature that the drag coefficient for a completely submerged sphere exhibits reduced drag when the boundary layer becomes turbulent. This reduction is somewhat more gradual for a sphere than that for a streamlined body because of the smaller contribution made by the pressure drag to the total drag of the streamlined body. A plot of the Reynolds Number, R_e versus the effective drag coefficient, C_D is shown in Figure 4. This data is for the locked sphere and towing mode (runs 163-174). The data indicates that a critical Reynolds Number of approximately 0.8×10^6 exists where the boundary layer becomes turbulent. There does not appear to be a region where C_D becomes independent of R_e at least over the limited ranges of R_e that were measured. It was felt that underwater photography would aid in gaining an understanding about the flow patterns around the Hydrosphere.



RUN #	V (ft sec^{-1})	C_D	Re (10^6)
163	5.08	0.46	1.02
164	5.08	0.53	1.02
165	3.80	0.34	0.76
166	5.56	0.63	1.11
167	6.25	0.67	1.25
168	5.36	0.71	1.07
169	7.32	0.74	1.46
170	5.17	0.53	1.03
171	7.50	0.78	1.50
172	4.69	0.46	0.94
173	6.67	0.68	1.33
174	3.26	0.48	0.65

Figure (4) : Plot of C_D vs Reynolds number for locked rotor

An underwater camera box shown in Figure 2 was constructed of ½" thick plexiglass for the 16 mm Bell & Howell movie camera. This box has an optical glass face which accommodates all three lenses of the turret. A crank on the side allows the camera to be rewound while underwater. The standard shutter release is activated by a spring loaded button.

For underwater photography the lenses were set to focus nearer than in air because of the change in index of refraction in going from water to air. Filming speed was 2X and 4X the normally used 16 frames per second. This was done in order to better resolve the flow characteristics. The lens' apertures were adjusted to account for this and for the slightly reduced light intensity underwater.

Underwater movies of the operation of the Hydrosphere were taken at Lake Tahoe which has extremely clear water. All camera work was done by a scuba diver in about twenty feet of water. The diver surfaced between runs in order to coordinate his function with the Hydrosphere crew.

Two 100 foot rolls of color film were made of the Hydrosphere operating self powered and towed/powered with a range of speeds over the 150 foot course.

The developed films have been reviewed for general qualitative information about the flows around the sphere. Air bubbles, generated at the front of the sphere, are carried with the water and act as flow tracers. Figure 5 shows bubbles in the areas of the vanes and between the keel bands. These bubbles typically flow to the points of least pressure within about 20^{o} of sphere revolution after entering the water, and stay attached until they are carried out of the water at the rear of the sphere. The bubbles in the keel band area slowly migrate in the direction of the fluid flow in some cases. The most interesting results, however, show total separation of flow from the keel bands and vanes in some cases. An example of this is shown in Figure 6 where ribbons of bubbles can be seen leaving

Figure (5) - Underwater photograph showing air bubbles in the area of the vanes and the keel band.

Figure (6) - Underwater photograph showing ribbons of bubbles leaving the sphere surface near the keel bands.

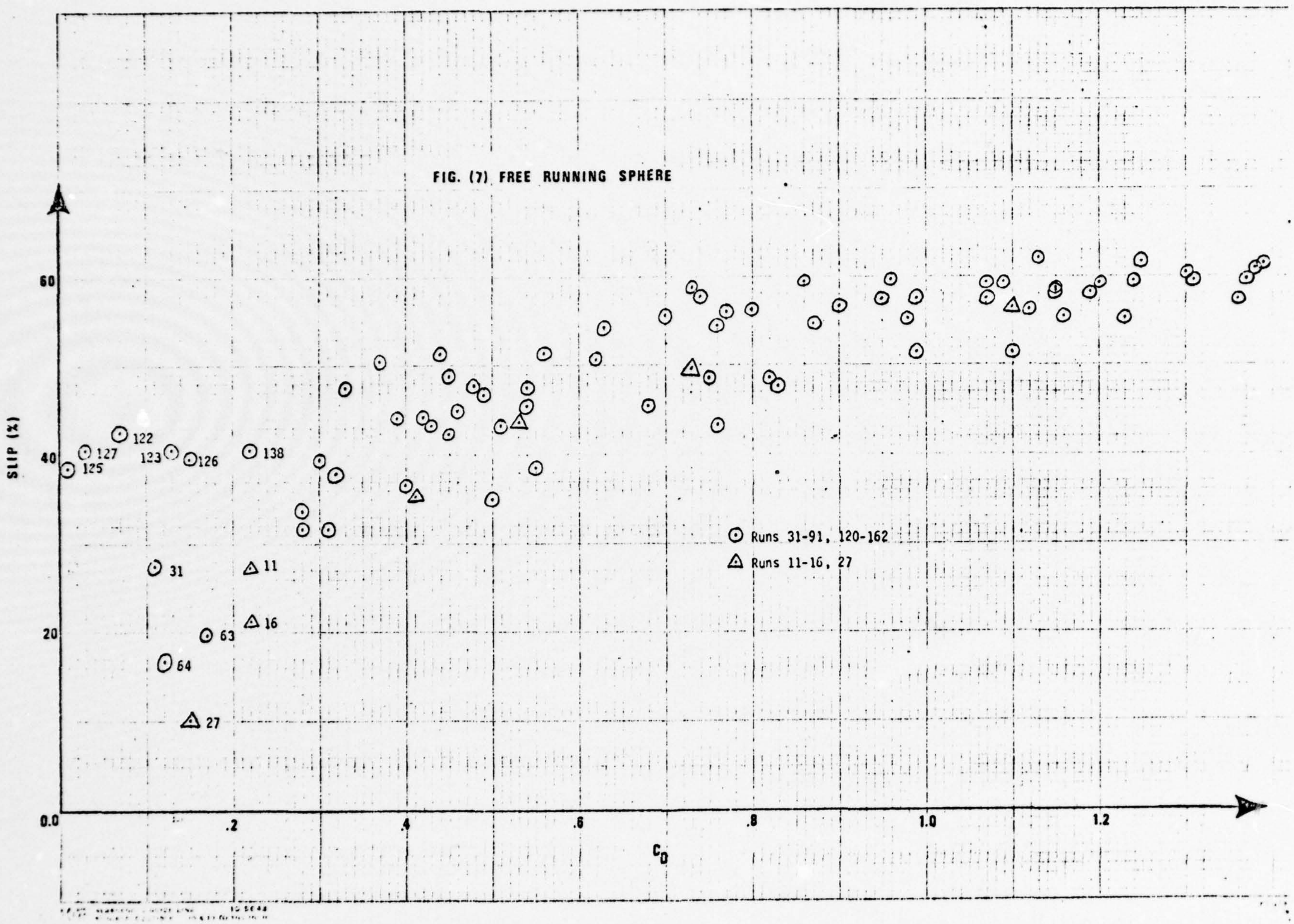
the sphere from the keel bands. This was not observed for the center section of the sphere surface.

In some cases the exhaust from the tow boat left many small bubbles well distributed through the water, which imporoved flow observation.

These movies were a satisfactory first attempt at underwater work and demonstrate that significant information of this type can be derived in an effective manner. It should be noted that these still photos were rephotographed from the projected movie film and have lost some detail in the processing. The actual movie films are far more graphic and easier to study.

Another plot of interest is a comparison of the drag coefficient C_D and slip, S. A plot of runs for the Hydrosphere operating in a self propelled, free running mode is shown in Figure 7 (runs 11-16,27, 31-91 and 120-162, inclusive). There is a definite interesting relationship between the effective drag coefficient, C_D and slip. The drag is very sensitive to slip and increases very rapidly for slippage above approximately 40%. More important is the very definite "dual mode" characteristic observed in Figure 7. The Hydrosphere can operate very efficiently even at a higher slip, however a corresponding price is paid in the center line velocity. This fact was confirmed by observing the Hydrosphere's applied power and recording the slip on film over the 150 ft course. The data was also supported by observing the changes in the wave generation characteristics for these runs. The Hydrosphere can develop a mode wherein the drag is greatly reduced and yet the center line velocity is increased. This is clearly shown in runs 11, 16, 31, 27, 63 and 64. During the first analysis it appeared that there was a smooth relationship between the slip and C_D; however, as the data were analyzed it became apparent that a dual mode definitely exists. Experimental error would not account for this

FIG. (7) FREE RUNNING SPHERE



phenomenon since the slip measurements are recorded on film and hence are easily and accurately determined; and also the power measurements are verified by observing from the film the magnitudes of the wave generative characteristics. For example, runs 123, 31, and 64 did exhibit approximately the same wave generating characteristics; however, the slip varied from 40% down to 10%. There was also a corresponding increase in the centerline velocity from 4.23 ft/sec for run 123 to 6.45 ft/sec for run 27.

This data supports the theory that boundary layer control may be the significant factor for Hydrosphere performance. It is not completely understood just how one maintians the low slip, higher velocity mode; however, it does merit further study. It is interesting to note that the most efficient runs occurred when the Hydrosphere was operated at an angular velocity of

$$.31 \leq \omega \leq .39 \text{ (rev/sec)}$$

A tabulation of these runs is shown in Table I.

There is another set of curves that can help to compare the Hydrosphere to other types of water craft, that is, a plot of the drag-lift coefficient, η, versus the Froude Number, F_r. These plots , Figures (8a, 8b) cover the data gathered in the field running self-propelled mode (runs 1-30, 31-91, and 120-162) and the towing plus self-propelled modes (runs 17-22, and 92-119). The question of data scatter has been resolved as can be seen in Figure 8. The Hydrosphere does actually exhibit a wide range of operating characteristics when one compares η_t with F_r. In fact it appears doubtful that the Hydrosphere can be adequately classified using only this type of classical comparison for the watercraft. It does suggest, however, that the Hydrosphere concept can be utilized by special design for a wide range of applications and operating conditions.

Run #	ω(rev/sec)	C_D
11	.36	.22
16	.34	.22
27	.32	.15
31	.38	.11
63	.39	.17
64	.36	.12
122	.34	.07
123	.32	.13
125	.31	.01
126	.34	.15
127	.32	.03
138	.35	.22

Table I

Tabulation of runs showing drag values, C_D below 0.23.

Free Running Sphere

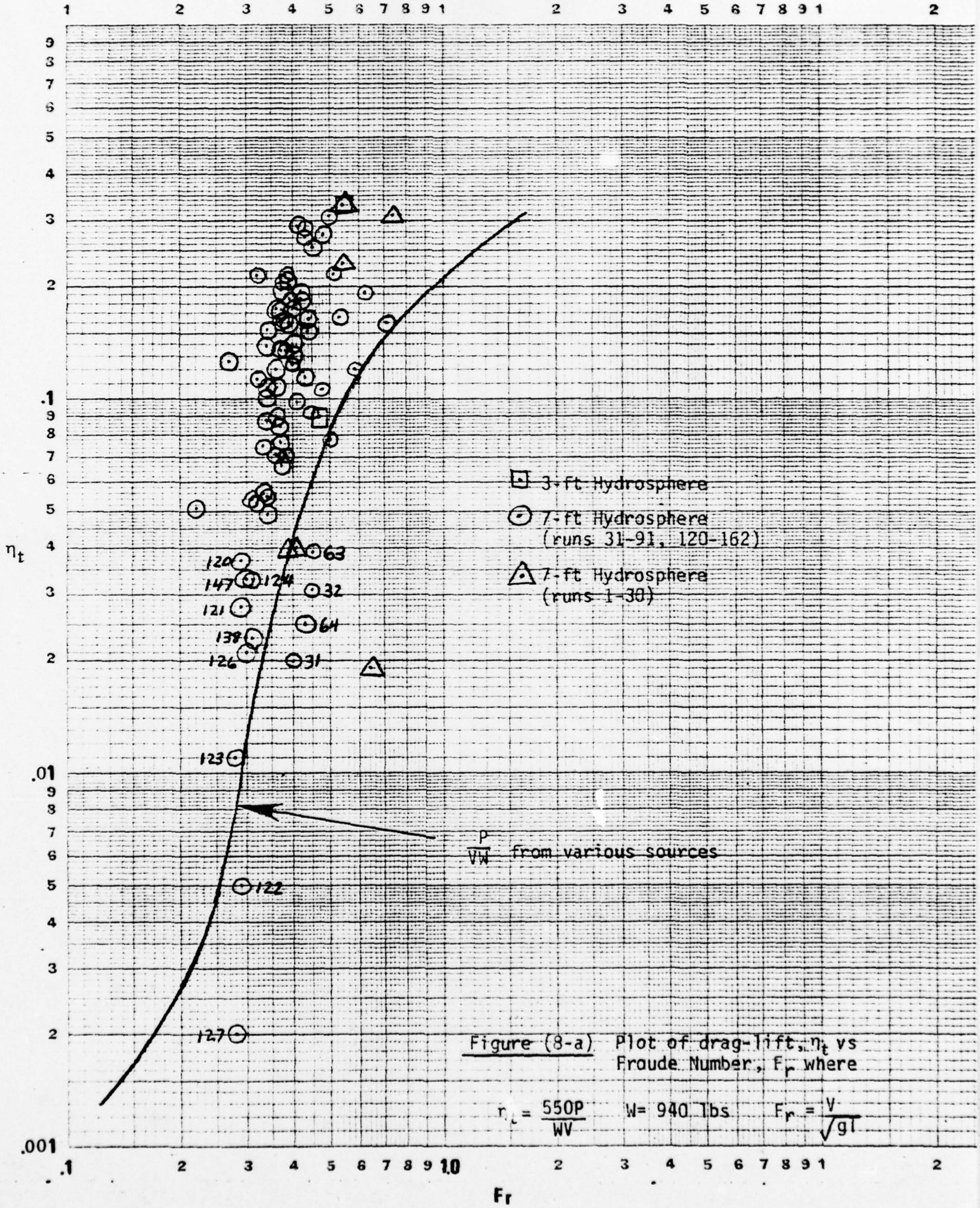


Figure (8-a) Plot of drag-lift, η_t vs Froude Number, F_r where

$\eta_t = \frac{550P}{WV}$ W= 940 lbs $F_r = \frac{V}{\sqrt{gl}}$

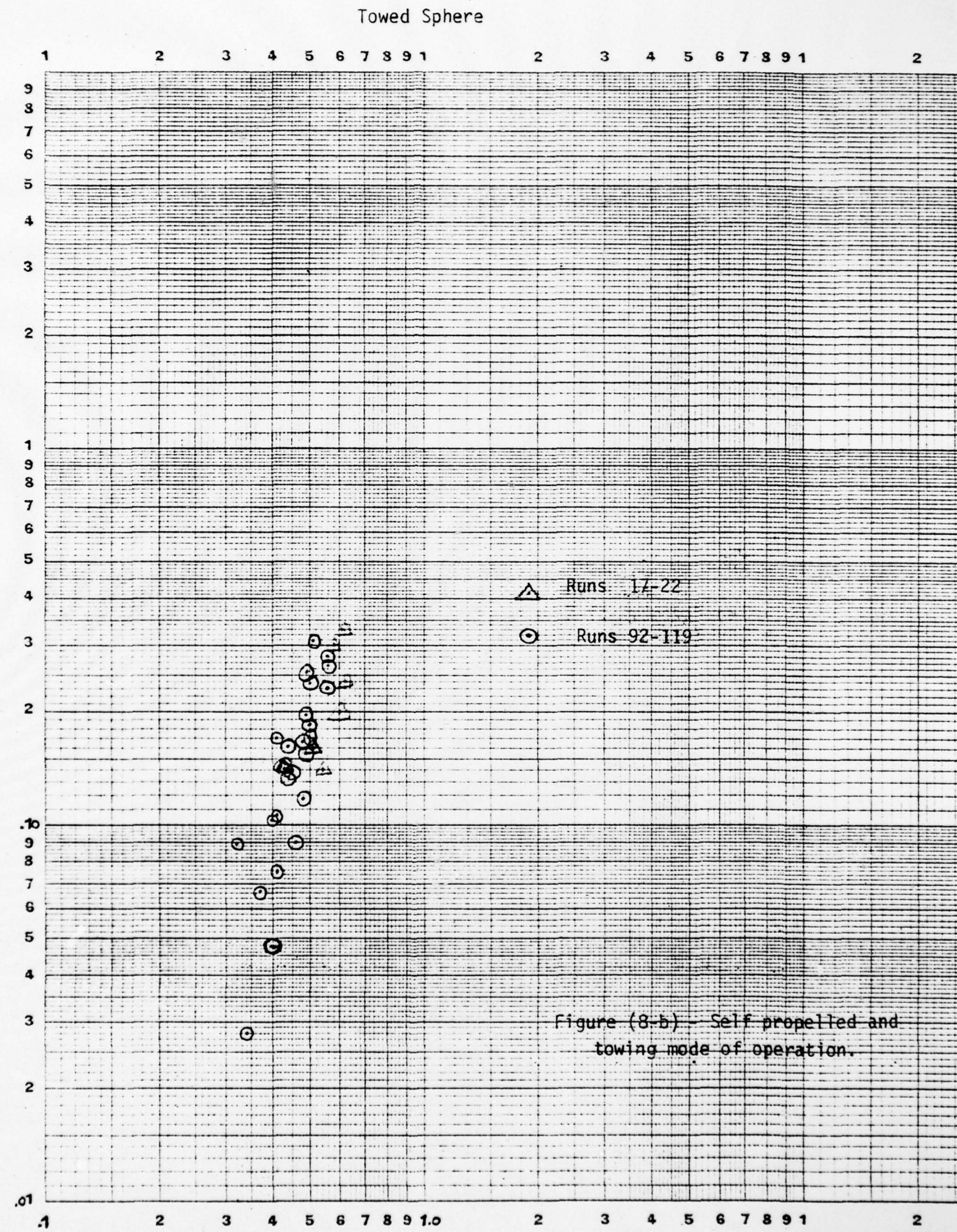


Figure (8-b) - Self propelled and towing mode of operation.

IV. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The Hydrosphere concept has been evaluated in detail and attempts made to quantify performance parameters. Extensive experimental data have been gathered and analyzed in an effort to describe and predict Hydrosphere performance characteristics. This new propulsion concept exhibits very complex flow characteristics, especially when compared to the more conventional watercraft. The work accomplished to date does, however, allow several conclusions to be reached.

(a) The Hydrosphere concept produces a stable operating system.

(b) Excellent lift-drag ratios can be obtained even at significant slip; however, when speed is of concern additional consideration must be given to the slip parameter.

(c) The Hydrosphere exhibits definite "multi-mode" characteristics. This means that the craft can be operated in a low slip and correspondingly higher velocity mode, that is quite different from that of a conventional planing watercraft.

(d) The Hydrosphere can be operated over a wide range of velocity and drag-lift ratios. The concept provides a number of interesting alternatives for proposing new types of multi terrain vehicles.

(e) It is not understood at this time what operating parameters are the most critical to operating the Hydrosphere in the highly efficient low slip mode.

(f) The rolling sphere was less susceptible to wind loading than was the "locked" sphere. Also the rolling sphere developed less total drag than the locked sphere.

(g) The Hydrosphere is basically a boundary control type watercraft. It has been shown that there are definite modes wherein highly

efficient low slip operation can be achieved. The effects of towing were not very great in that little was gained by applying significant towing power to the sphere. It is felt that this is because of the experimental difficulty in towing the Hydrosphere with the proper degree of forward slip, which may be necessary to achieve the low drag mode.

(h) The 7' Hydrosphere "optimum" mode occurred in all cases when the angular velocity, ω, was between $.32 \leq \omega \leq .39$.

(i) There is sufficient data favorable to the Hydrosphere concept to justify further research.

There are still several important questions to be answered before one can understand and characterize the Hydrosphere concept. The basic questions are:

- How to model and scale Hydrospheres since it is still not clear what methods or parameters can be used for scaling performance to larger spheres. The general wave generating characteristics appear to be similar when one observes the wave generating performance of the 3', 7' and 10' Hydrospheres; however, the effect of loading has not been determined. There is sufficient evidence to warrant further study into the Hydrosphere concept.

The next step in the Hydrosphere program should be a special set of tests designed to evaluate Hydrosphere performance under various loading conditions. This was not possible to accomplish within the present experimental project because the 7 ft Hydrosphere model was already operating at a 17% submergence level and it was not possible to lighten the model. It should be possible, however, to operate and gather performance data on a body of water having a greater density. This has the same effect as less load, the case of greatest interest.

For example, performance runs on the Great Salt Lake in Utah could provide a suitable set of data to evaluate Hydrosphere performance under controlled loading conditions.

Such a set of data could also provide a basis for determining whether or not loading is a significant factor to having the Hydrosphere operate in its higher velocity-lower slip mode. It is felt that these runs could be accomplished rapidly for less than $8,500. The Hydrosphere model and support equipment (with personnel) could be moved to Salt Lake for a week or ten day period of testing.

The Hydrosphere concept should be of interest to the Navy based on the already demonstrated performance characteristics. For example, it is possible with the present data to consider the Hydrosphere as a low velocity, efficient watercraft capable of moving cargo over swamp areas and inland waterways. Once the cargo has been delivered the craft could then achieve a higher velocity for the return trip to the cargo staging area. This concept, for example, could provide the Navy with a watercraft capable of transporting standard containers over multi terrain conditions. It is also felt that the variable loading tests described above could greatly aid in helping to determine and predict Hydrosphere performance especially since multi mode performance has been experimentally observed.

APPENDIX A

This Appendix includes the entire set of data for the extended Hydrosphere project. Runs 11 through 30 were presented and discussed in the Final Report Part II, dated October 20, 1975. The new data were gathered in six (6) separate days of testing at Boca Reservoir and Lake Tahoe, Nevada.

Run Numbers (inclusive)	Date	Location	Notes
31-38	9/7/76	Boca	Self propelled, free running
39-71	9/21/76	Boca	Self propelled, free running
72-91	9/28/76	Boca	Self propelled, free running
92-119	10/19/76	Lake Tahoe	Self propelled and towed
120-162	10/29/76	Lake Tahoe	Self propelled, free running
163-174	10/29/76	Lake Tahoe	Tow locked sphere
175-181	10/29/76	Lake Tahoe	Tow free rolling
182-186	10/29/76	Lake Tahoe	Tow reverse free rolling
187-205	10/30/76	Lake Tahoe	Underwater film, runs 202-205 were self propelled, towing

Run Numbers (inclusive)	Date	Location	Notes
11-16, 27	9/23/75	Boca	Self propelled, free running
17-22, 26	9/23/75	Boca	Self propelled and towed
23-25	9/23/75	Boca	Tow locked sphere
28-30	9/23/75	Boca	Tow free rolling

Data taken Sept. 23, 1975

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
11	6.2	17.0	.36	27.4	5.88	4.0	8.0	—	0	0	.37	.37	.39	.22	.04
12	9.0	12.4	.73	50.0	8.06	5.5	36.4	—	0	0	3.2	3.2	.54	.73	.23
13	7.0	10.3	.68	35.7	9.71	6.6	38.0	—	0	0	3.1	3.1	.65	.41	.19
14	10.5	12.5	.84	57.1	8.00	5.5	45.6	—	0	0	4.5	4.5	.53	1.1	.33
15	8.0	9.0	.89	43.8	11.11	7.6	63.0	—	0	0	5.9	5.9	.74	.53	.31
16	5.7	16.6	.34	21.1	6.02	4.1	8.9	—	0	0	.39	.39	.40	.22	.04
17	7.0	13.0	.54	35.7	7.69	5.2	17.3	0	63	.88	1.2	2.1	.51	.55	.16
18	8.4	11.0	.76	46.4	9.09	6.2	37.0	0	106	1.75	3.4	5.2	.61	.83	.33
19	3.8	11.1	.34	-15.6	9.00	6.1	3.9	0	174	2.85	.17	3.0	.60	.49	.20
20	6.3	10.8	.58	28.6	9.26	6.3	30.5	0	138	2.32	2.2	4.5	.62	.67	.28
21	8.7	11.5	.76	48.3	8.70	6.9	33.1	0	91	1.44	3.1	4.5	.58	.82	.30
22	5.0	12.4	.40	10.0	8.06	5.5	small	0	129	1.89	small	1.89	.54	.43	.14
23	0.0	22.5	0	—	4.44	3.0	—	0	54	.44	—	.44	.30	.60	.06

Data taken Sept. 23, 1975

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
24	0.0	16.0	0	–	6.25	4.3	–	0	100	1.14	–	1.14	.42	.56	.11
25	0.0	13.1	0	–	7.63	5.2	–	0	168	2.33	–	2.33	.51	.63	.18
26	9.2	10.6	.87	51.1	9.43	6.4	37.9	0	200	3.43	4.0	7.43	.63	1.1	.46
27	5.0	15.5	.32	10.0	6.45	4.4	8.0	—	0	0	.33	.33	.43	.15	.03
28	3.1	14.0	.22	-31.1	7.14	4.9	–	0	54	.70	–	.70	.48	.23	.06
29	3.2	12.5	.26	-28.9	8.00	5.5	–	0	96	1.40	–	1.40	.53	.33	.10
30	3.2	11.4	.28	-28.9	8.77	6.0	–	0	173	2.76	–	2.76	.58	.49	.18

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
31	9.4	25.0	.38	27.43	6.0	4.09	4.0	—	—	0	.20	.20	.40	0.11	.020
32	17.0	22.0	.77	59.87	6.82	4.65	38.9	—	—	0	3.63	3.63	.45	1.37	.311
33	10.8	22.0	.49	36.84	6.82	4.65	16.9	—	—	0	1.07	1.07	.45	.40	.092
34	10.3	20.0	.52	33.77	7.50	5.11	15.0	—	—	0	1.00	1.00	.50	.28	.078
35	12.0	21.0	.57	43.16	7.14	4.87	17.9	—	—	0	1.31	1.31	.48	.43	.107
36	11.8	16.0	.74	42.19	9.38	6.39	34.0	—	—	0	3.08	3.08	.62	.45	.192
37	14.0	21.0	.67	51.28	7.14	4.87	—	—	—	0	—	—	.48	—	—
38	8.0	28.5	.28	14.73	5.26	3.59	—	—	—	0	—	—	.35	—	—
39	6.5	19.0	.34	-4.94	7.89	5.38	—	—	—	0	—	—	.53	—	—
40	12.0	23.0	.52	43.16	6.52	4.45	—	—	—	0	—	—	.43	—	—
41	9.5	22.0	.43	28.20	6.82	4.65	—	—	—	0	—	—	.45	—	—
42	11.0	26.0	.42	37.99	5.77	3.93	—	—	—	0	—	—	.38	—	—
43	9.0	21.0	.43	24.21	7.14	4.87	—	—	—	0	—	—	.48	—	—

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
44	10.5	23.5	.45	35.04	6.38	4.35	—	—	—	0	—	—	.43	—	—
45	9.5	16.0	.59	28.20	9.38	6.39	—	—	—	0	—	—	.62	—	—
46	12.5	23.0	.54	45.43	6.52	4.45	—	—	—	0	—	—	.43	—	—
47	12.0	22.0	.55	43.16	6.82	4.65	—	—	—	0	—	—	.45	—	—
48	10.5	19.0	.55	35.04	7.89	5.38	—	—	—	0	—	—	.53	—	—
49	13.5	21.5	.63	49.47	6.98	4.76	—	—	—	0	—	—	.46	—	—
50	11.5	19.0	.61	40.68	7.89	5.38	—	—	—	0	—	—	.53	—	—
51	13.5	21.5	.63	49.47	6.98	4.76	—	—	—	0	—	—	.46	—	—
52	11.5	18.5	.62	40.68	8.11	5.53	—	—	—	0	—	—	.54	—	—
53	12.0	18.5	.65	43.16	8.11	5.53	—	—	—	0	—	—	.54	—	—
54	10.5	15.0	.70	35.04	10.00	6.82	—	—	—	0	—	—	.67	—	—
55	14.0	21.0	.67	51.28	7.14	4.87	—	—	—	0	—	—	.48	—	—
56	12.5	18.0	.69	45.43	8.33	5.68	—	—	—	0	—	—	.56	—	—

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
57	15.5	20.5	.76	55.99	7.32	4.99	—	—	—	0	—	—	.49	—	—
58	14.0	18.0	.78	51.28	8.33	5.68	—	—	—	0	—	—	.56	—	—
59	14.5	19.5	.74	52.96	7.69	5.24	—	—	—	0	—	—	.51	—	—
60	12.0	18.5	.65	43.16	8.11	5.53	—	—	—	0	—	—	.54	—	—
61	13.0	18.5	.70	47.53	8.11	5.53	—	—	—	0	—	—	.54	—	—
62	10.0	17.0	.59	31.79	8.82	6.62	23.5	—	—	0	1.76	1.76	.59	0.31	0.12
63	8.5	22.0	.39	19.75	6.82	4.65	8.9	—	—	0	.45	.45	.45	.17	.039
64	8.2	23.0	.36	16.81	6.52	4.45	6.0	—	—	0	.28	.28	.43	.12	.025
65	12.0	22.5	.53	43.16	6.67	4.55	27.9	—	—	0	1.87	1.87	.44	.76	.164
66	12.5	23.0	.54	45.43	6.52	4.45	18.0	—	—	0	1.26	1.26	.43	.54	.113
67	11.1	19.0	.58	38.55	7.89	5.38	30.9	—	—	0	2.24	2.24	.53	.55	.166
68	15.6	22.0	.71	56.27	6.82	4.65	34.0	—	—	0	2.97	2.97	.45	1.12	.255
69	13.3	19.5	.68	48.71	7.69	5.24	33.9	—	—	0	2.85	2.85	.51	.75	.217

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
70	15.6	21.0	.74	56.27	7.14	4.87	37.0	—	—	0	3.34	3.34	.48	1.10	.274
71	10.0	14.0	.71	31.79	10.71	7.31	32.4	—	—	0	2.85	2.85	.71	.28	.16[illegible]
72	14.0	26.0	.54	51.28	5.77	3.93	10.0	—	—	0	.70	.70	.38	.44	.07
73	12.2	29.0	.42	44.09	5.17	3.53	8.9	—	—	0	.49	.49	.34	.42	.05[illegible]
74	16.6	22.5	.74	58.91	6.67	4.55	19.0	—	—	0	1.80	1.80	.44	.73	.158
75	15.4	25.0	.62	55.71	6.00	4.09	15.9	—	—	0	1.26	1.26	.40	.70	.123
76	18.0	20.0	.90	62.10	7.50	5.11	36.0	—	—	0	3.96	3.96	.50	1.13	.309
77	17.7	23.0	.77	61.46	6.52	4.45	33.9	—	—	0	3.21	3.21	.43	1.39	.288
78	18.2	24.5	.74	62.52	6.12	4.17	33.0	—	—	0	3.03	3.03	.41	1.58	.290
79	17.5	23.5	.74	61.02	6.38	4.35	32.7	—	—	0	2.99	2.99	.43	1.38	.270
80	12.5	29.0	.43	45.43	5.17	3.53	14.0	—	—	0	.78	.78	.34	.68	.088
81	12.0	27.0	.44	43.16	5.56	3.79	12.9	—	—	0	.73	.73	.37	.51	.077
82	13.3	27.0	.49	48.71	5.56	3.79	10.0	—	—	0	.64	.64	.37	.45	.067

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_c
83	13.8	27.5	.50	50.57	5.45	3.72	12.9	—	—	0	.84	.84	.36	.62	.090
84	12.8	27.5	.47	46.71	5.45	3.72	11.0	—	—	0	.66	.66	.36	.49	.071
85	15.0	24.0	.63	54.52	6.25	4.26	25.9	—	—	0	2.06	2.06	.42	1.01	.193
86	16.2	25.0	.65	57.89	6.00	4.09	16.0	—	—	0	1.34	1.34	.40	.74	.131
87	16.0	25.0	.64	57.37	6.00	4.09	21.9	—	—	0	1.79	1.79	.40	.99	.175
88	15.6	25.0	.62	56.27	6.00	4.09	16.0	—	—	0	1.44	1.44	.40	.80	.140
89	15.2	24.0	.63	55.12	6.25	4.26	24.9	—	—	0	1.99	1.99	.42	.98	.186
90	17.0	26.0	.65	59.87	5.77	3.93	25.6	—	—	0	2.10	2.10	.38	1.31	.213
91	16.0	24.5	.65	57.37	6.12	4.17	—	—	—	0	—	—	.41	—	—
92	4.6	29.0	.16	-48.29	5.17	3.53	2.1	27.5	25	.21	.04	.25	.34	.22	.028
93	4.5	25.0	.18	-51.58	6.00	4.09	small	27.0	50	.49	0	.49	.40	.27	.048
94	8.6	21.5	.40	20.68	6.98	4.76	4.9	27.5	72	.81	.26	1.07	.46	.38	.090
95	4.5	31.0	.15	-51.58	4.84	3.30	2.0	27.3	90	.70	.04	.74	.32	.79	.089

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	F_r	C_D	η_t
96	10.4	21.0	.50	34.41	7.14	4.87	17.9	26.3	26	.30	1.14	1.44	.48	.47	.118
97	12.9	24.0	.54	47.12	6.25	4.26	3.9	29.0	125	1.24	.27	1.52	.42	.75	.142
98	11.7	19.5	.60	41.70	7.69	5.24	22.9	29.5	190	2.31	1.75	4.06	.51	1.07	.309
99	9.6	18.0	.53	28.94	8.33	5.68	15.9	22.5	208	2.91	1.09	4.00	.56	.83	.281
100	7.7	18.0	.43	11.41	8.33	5.68	8.9	22.0	198	2.78	.50	3.28	.56	.68	.231
101	9.0	18.5	.49	24.21	8.11	5.53	–	–	210	0	–	–	.54	–	–
102	11.4	18.0	.63	40.16	8.33	5.68	27.9	21.5	110	1.55	2.22	3.77	.56	.78	.265
103	8.6	20.5	.42	20.68	7.32	4.19	9.9	24.4	115	1.39	.54	1.93	.49	.59	.154
104	9.4	20.0	.47	27.43	7.50	5.11	12.9	26.0	115	1.41	.78	2.19	.50	.62	.171
105	8.6	21.0	.41	20.68	7.14	4.87	11.9	25.0	120	1.41	.63	2.04	.48	.67	.167
106	8.8	20.0	.44	22.49	7.50	5.11	13.9	24.0	126	1.57	.79	2.36	.50	.67	.184
107	12.8	20.0	.64	46.71	7.50	5.11	23.9	25.5	90	1.11	1.94	3.05	.50	.87	.238
108	13.9	20.5	.68	50.93	7.32	4.99	23.9	25.0	93	1.12	2.05	3.18	.49	.97	.254

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
109	12.5	20.5	.61	45.43	7.32	4.99	20.9	22.3	67	.82	1.63	2.45	.49	.75	.196
110	12.5	22.0	.57	45.43	6.82	4.65	15.9	26.0	40	.45	1.16	1.61	.45	.61	.138
111	12.5	22.5	.56	45.43	6.67	4.55	18.9	25.8	45	.49	1.35	1.84	.44	.74	.161
112	12.2	22.5	.54	44.09	6.67	4.55	17.9	28.0	26	.28	1.25	1.52	.44	.62	.133
113	13.5	23.5	.57	49.47	6.38	4.35	16.9	27.5	28	.29	1.25	1.54	.43	.71	.141
114	13.1	23.5	.56	47.93	6.38	4.35	18.9	27.0	20	.21	1.35	1.56	.43	.72	.143
115	14.5	24.5	.59	52.96	6.12	4.17	20.9	28.0	20	.20	1.58	1.78	.41	.93	.170
116	12.7	24.5	.52	46.29	6.12	4.17	12.9	28.5	25	.24	.87	1.11	.41	.58	.106
117	11.8	24.5	.48	42.19	6.12	4.17	11.9	28.0	4	.04	.74	.78	.41	.41	.075
118	12.0	27.0	.44	43.16	5.56	3.79	9.9	29.0	8	.07	.57	.64	.37	.45	.067
119	11.0	25.0	.44	37.99	6.00	4.09	8.9	23.0	55	.55	.51	1.06	.40	.59	.103
120	12.2	34.0	.36	44.09	4.41	3.01	6.0	—	—	0	.28	.28	.29	.39	.037
121	11.3	34.0	.33	39.63	4.41	3.01	4.9	—	—	0	.21	.21	.29	.30	.028

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
122	11.9	35.0	.34	42.68	4.29	2.92	1.0	—	—	0	.04	.04	.29	.07	.005
123	11.5	35.5	.32	40.68	4.23	2.88	1.9	—	—	0	.08	.08	.28	.13	.011
124	11.0	32.5	.34	37.99	4.62	3.15	6.0	—	—	0	.26	.26	.31	.32	.033
125	11.1	36.0	.31	38.55	4.17	2.84	0.1	—	—	0	.004	.004	.28	.01	.0006
126	11.3	33.5	.34	39.63	4.48	3.05	2.5	—	—	0	.11	.11	.30	.15	.021
127	11.5	35.5	.32	40.68	4.23	2.88	0.4	—	—	0	.017	.017	.28	.03	.002
128	13.3	29.0	.46	48.71	5.17	3.53	16.0	—	—	0	.95	.95	.34	.82	.108
129	13.8	29.0	.48	50.57	5.17	3.53	6.9	—	—	0	.43	.43	.34	.37	.049
130	17.2	27.0	.64	60.34	5.56	3.79	23.0	—	—	0	1.86	1.86	.37	1.30	.196
131	15.0	28.0	.54	54.52	5.36	3.65	13.9	—	—	0	.97	.97	.36	.76	.106
132	14.0	27.0	.52	51.28	5.56	3.79	12.0	—	—	0	.81	.81	.37	.56	.085
133	16.7	27.5	.61	59.15	5.45	3.72	20.9	—	—	0	1.62	1.62	.36	1.20	.174
134	16.1	27.0	.60	57.63	5.56	3.79	20.0	—	—	0	1.53	1.53	.37	1.07	.161

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
135	15.5	29.0	.53	55.99	5.17	3.53	12.9	—	—	0	.89	.89	.34	.77	.101
136	15.1	26.5	.57	54.83	5.66	3.86	18.0	—	—	0	1.32	1.32	.38	.87	.130
137	15.3	29.0	.53	55.42	5.17	3.53	19.9	—	—	0	1.34	1.34	.34	1.16	.152
138	11.5	32.5	.35	40.68	4.62	3.15	4.0	—	—	0	.83	.83	.31	.22	.02[illegible]
139	17.0	37.5	.45	59.87	4.00	2.73	14.9	—	—	0	.87	.87	.27	1.63	.12[illegible]
140	13.0	27.5	.47	47.53	5.45	3.72	18.5	—	—	0	1.12	1.12	.36	.83	.120
141	15.2	28.0	.54	55.12	5.36	3.65	22.9	—	—	0	1.58	1.58	.36	1.23	.172
142	15.8	27.0	.59	56.83	5.56	3.79	17.0	—	—	0	1.28	1.28	.37	.90	.135
143	16.6	27.0	.61	58.91	5.56	3.79	20.9	—	—	0	1.64	1.64	.37	1.15	.173
144	16.9	25.5	.66	59.64	5.88	4.01	25.0	—	—	0	2.10	2.10	.39	1.24	.209
145	14.1	31.0	.45	51.62	4.84	3.30	15.9	—	—	0	.93	.93	.32	.99	.112
146	12.4	30.0	.41	44.99	5.00	3.41	9.0	—	—	0	.48	.48	.33	.46	.056
147	13.0	33.5	.39	47.53	4.48	3.05	4.9	—	—	0	.25	.25	.30	.33	.033

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
148	10.5	32.0	.33	35.04	4.69	3.20	10.0	—	—	0	.43	.43	.31	.50	.054
149	13.1	31.5	.42	47.93	4.76	3.25	7.9	—	—	0	.43	.43	.32	.48	.053
150	16.8	26.5	.63	59.40	5.66	3.86	20.0	—	—	0	1.62	1.62	.38	1.07	.167
151	17.0	46.5	.37	59.87	3.30	2.25	5.9	—	—	0	.29	.29	.22	.96	.051
152	18.7	31.5	.59	63.52	4.76	3.25	23.0	—	—	0	1.74	1.74	.32	1.93	.214
153	14.9	30.5	.49	54.22	4.92	3.35	9.9	—	—	0	.63	.63	.33	.63	.075
154	17.8	25.5	.70	61.68	5.88	4.01	24.0	—	—	0	2.12	2.12	.39	1.25	.211
155	16.8	26.5	.63	59.40	5.66	3.86	15.9	—	—	0	1.30	1.30	.38	.86	.134
156	16.8	25.5	.66	59.40	5.88	4.01	22.0	—	—	0	1.85	1.85	.39	1.09	.184
157	16.4	26.0	.63	58.41	5.77	3.93	22.9	—	—	0	1.84	1.84	.38	1.15	.187
158	16.3	25.5	.64	58.15	5.88	4.01	25.0	—	—	0	2.02	2.02	.39	1.19	.201
159	16.0	27.0	.59	57.37	5.56	3.79	25.9	—	—	0	1.94	1.94	.37	1.36	.204
160	16.0	25.5	.63	57.37	5.88	4.01	20.0	—	—	0	1.61	1.61	.39	.95	.160

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RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
161	14.0	29.5	.47	51.28	5.08	3.47	19.9	—	—	0	1.21	1.21	.34	1.10	.139
162	13.0	24.5	.53	47.53	6.12	4.17	15.0	—	—	0	1.03	1.03	.41	.54	.098
163	0	29.5	0	—	5.08	3.47	—	26	60	.50	0	.50	.34	.46	.058
164	0	29.5	0	—	5.08	3.47	—	26	70	.58	0	.58	.34	.53	.06[illegible]
165	0	39.5	0	—	3.80	2.59	—	26	25	.16	0	.16	.25	.34	.025
166	0	27.0	0	—	5.56	3.79	—	26	99	.90	0	.90	.37	.63	.095
167	0	24.0	0	—	6.25	4.26	—	26	133	1.36	0	1.36	.42	.67	.127
168	0	28.0	0	—	5.36	3.65	—	26	104	.91	0	.91	.36	.71	.099
169	0	20.5	0	—	7.32	4.99	—	26	203	2.43	0	2.43	.49	.74	.194
170	0	29.0	0	—	5.17	3.53	—	26	72	.61	0	.61	.34	.53	.06[illegible]
171	0	20.0	0	—	7.50	5.11	—	26	225	2.76	0	2.76	.50	.78	.215
172	0	32.0	0	—	4.69	3.20	—	26	52	.40	0	.40	.31	.46	.050
173	0	22.5	0	—	6.67	4.55	—	26	153	1.67	0	1.67	.44	.68	.146

* NOT RECORDED

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
174	0	46.0	0	—	3.26	2.22	—	26	26	.14	0	.14	.22	.48	.025
175	*	21.5	—	—	6.98	4.76	—	26	152	1.73	0	1.73	.46	.61	.145
176	*	27.5	—	—	5.45	3.72	—	26	50	.45	0	.45	.36	.33	.048
177	10	20.5	.49	31.78	7.32	4.99	—	26	242	2.89	0	2.89	.49	.89	.231
178	*	24.0	—	—	6.25	4.26	—	26	150	1.53	0	1.53	.42	.75	.143
179	8	23.0	.35	14.75	6.52	4.45	—	26	118	1.26	0	1.26	.43	.54	.113
180	*	32.5	—	—	4.62	3.15	—	26	28	.21	0	.21	.31	.26	.027
181	*	24.5	—	—	6.12	4.17	—	26	85	.85	0	.85	.41	.44	.081
182	*	30.0	—	—	5.00	3.41	—	26	42	.34	0	.34	.33	.33	.040
183	8	21.0	.38	14.75	7.14	4.87	—	26	208	2.43	0	2.43	.48	.80	.199
184	8	25.0	.32	14.75	6.00	4.09	—	26	108	1.06	0	1.06	.40	.59	.103
185	7	22.5	.31	2.57	6.67	4.55	—	26	160	1.74	0	1.74	.44	.71	.153
186	7	31.0	.23	2.57	4.84	3.30	—	26	30	.24	0	.24	.32	.25	.029

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
187	10.0	42.0	.24	31.79	3.57	2.44	—	—	—	0	—	—	.24	—	—
188		RUN ABORTED DUE TO ENGINE SHUT DOWN													
189	10.5	42.0	.25	35.04	3.57	2.44	—	—	—	0	—	—	.24	—	—
190	12.0	31.5	.38	43.16	4.76	3.25	—	—	—	0	—	—	.32	—	—
191	12.0	31.0	.39	43.16	4.84	3.30	—	—	—	0	—	—	.32	—	—
192	12.0	29.5	.41	43.16	5.08	3.47	—	—	—	0	—	—	.34	—	—
193	12.5	29.5	.42	45.43	5.08	3.47	—	—	—	0	—	—	.34	—	—
194	12.5	28.0	.45	45.43	5.36	3.65	—	—	—	0	—	—	.36	—	—
195	12.5	29.5	.42	45.43	5.08	3.47	—	—	—	0	—	—	.34	—	—
196	12.0	27.5	.44	43.16	5.45	3.72	—	—	—	0	—	—	.36	—	—
197	13.0	30.0	.43	47.53	5.00	3.41	—	—	—	0	—	—	.33	—	—
198	11.0	31.0	.35	37.99	4.84	3.30	—	—	—	0	—	—	.32	—	—
199	11.0	29.5	.37	37.99	5.08	3.47	—	—	—	0	—	—	.34	—	—

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
200	10.5	45.0	.23	35.04	3.33	2.27	*	—	—	0	—	—	.22	—	—
201	10.5	32.5	.32	35.04	4.62	3.15	*	—	—	0	—	—	.31	—	—
202	8.5	25.0	.34	19.75	6.00	4.09	*	26	38	.37	—	—	.40	.21	—
203	6.5	24.5	.27	-4.94	6.12	4.17	*	26	35	.35	—	—	.41	.18	—
204	7.5	27.0	.28	9.05	5.56	3.79	*	26	30	.27	—	—	.37	.19	—
205	8.5	21.0	.40	19.75	7.14	4.87	*	26	85	.99	—	—	.48	.33	—

* NOT MEASURED BECAUSE CAMERA WAS USED UNDERWATER, IN EACH CASE SPHERE POWER WAS VERY LOW.

APPENDIX B

Film Record

Film Record

Run #	Film Footage	Run #	Film Footage
31	0-17	74	27-40
32	17-36	75	40-53
33	36-53	76	53-64
34	53-72	77	64-75
35	72-86	78	75-87
36	86-105	79	87-96
37	none	80	none
38	none	81	5-8
39	on boat	82	8-19
40	on boat	83	19-30
.	.		
.	.	84	30-41
61	on boat	85	41-49
62	5-7	86	49-59
63	7-12	87	59-73
64	12-23	88	73-82
65	23-33	89	82-91
66	33-43	90	92-104
67	43-52	91	none
68	52-63	92	4-15
69	63-73	93	15-23
70	73-83	94	23-34
71	83-90	95	34-48
72	5-12	96	48-58
73	12-27	97	58-70

Run #	Film Footage	Run #	Film Footage
98	70-81	124	154-168
99	81-90	125	0-20
100	90 -	126	20-38
101	none	127	38-55
102	0-13	128	55-69
103	13-24	129	69-84
104	24-36	130	84-100
105	36-49	131	103-120
106	52-63	132	0-15
107	63-73	133	15-29
108	73-84	134	29-43
109	84-95	135	43-57
110	95-107	136	57-71
111	0-8	137	71-85
112	8-20	138	85-101
113	20-32	139	101-120
114	32-43	140	0-14
115	43-55	141	14-27
116	55-66	142	27-40
117	69-79	143	40-53
118	79-88	144	53-66
119	0-13	145	66-81
120	83-101	146	81-95
121	101-118	147	95-110
122	118-136	148	0-16
123	136-154	149	16-31

Run #	Film Footage
150	31-44
151	44-63
152	63-78
153	78-92
154	92-105
155	0-14
156	14-28
157	28-41
158	41-54
159	54-67
160	67-80
161	80-94
162	96-108
163	none
164	none
165	none
.	.
.	.
186	none
187	underwater
188	underwater
.	.
.	.
205	underwater

APPENDIX C

Computer Program Used to Reduce the

Hydrosphere Data.

```
COURSE LENGTH
? 150.0
ENTER NUMBER ØF RUNS TØ BE CØMPUTED
? 1
ENTER RUN,REV,TIME,THETA,FTØWR,THETAR
? 92,4.6,29,2.1,25,27.5


  RUN   ØMEGA  SLIP    FPS    MPH    HPS    TWHP   THP     FR     CD

   92   .16 -48.29   5.17   3.53    .04    .21    .25    .34    .22
    STØP

SRU       1.302 UNTS.

RUN CØMPLETE.
LNH

       PRØGRAM RØVER (INPUT,ØUTPUT,TAPE5=INPUT,TAPE6=ØUTPUT)
      DIMENSIØN RUN(50),REV(50),TIME(50),THETA(50),FTØW(50),
       ØMEGA(50),VCLFPS(50),VCLMPH(50),SPHHP(50),TØWHP(50),
       TØTHP(50),SLIP(50),CD(50),FR(50)
       DIMENSIØN THETAR(50),FTØWR(50)
       PI=355./113.
      INTEGER RUN
       WRITE (6,1)
     1 FØRMAT (*CØURSE LENGTH*)
       READ,CØURSE
       WRITE(6,2)
     2 FØRMAT (*ENTER NUMBER ØF RUNS TØ BE CØMPUTED*)
       READ,N
       WRITE (6,3)
     3 FØRMAT (*ENTER RUN,REV,TIME,THETA,FTØWR,THETAR*)
       DØ 10 I=1N
    10 READ,RUN(I),REV(I),TIME(I),THETA(I),FTØWR(I),THETAR(I)
       WRITE (6,5)
     5 FØRMAT (//)
       WRITE (6,6)
     6 FØRMAT(*  RUN   ØMEGA  SLIP    FPS    MPH    HPS    TWHP*,
       3X,*THP     FR     CD*)
       DØ 20 J=1,N
       RIDEAL=CØURSE/21.99
       ØMEGA(J)=REV(J)/TIME(J)
       VCLFPS(J)=CØURSE/TIME(J)
       VCLMPH(J)=VCLFPS(J)/(88./60.)
       SPHHP(J)=7.48*ØMEGA(J)*(SIN(PI*THETA(J)/180.))
       FTØW(J)=FTØWR(J)*CØS(PI*THETAR(J)/180.)
       TØWHP(J)=(CØURSE*FTØW(J))/(550.*TIME(J))
       TØTHP(J)=SPHHP(J)+TØWHP(J)
       SLIP(J)=(1-(RIDEAL/REV(J)))*100
       CD(J)=(120*TØTHP(J))/(VCLFPS(J)**3.)
       FR(J)=VCLFPS(J)/15.01
       WRITE (6,4) RUN(J),ØMEGA(J),SLIP(J),VCLFPS(J),VCLMPH(J),
       SPHHP(J),TØWHP(J),TØTHP(J),FR(J),CD(J)
     4 FØRMAT (/,2X,I3,9F7.2)
    20 CØNTINUE
       STØP
       END
READY.
BYE

BH42E13   LØG ØFF     16.49.49.
BH42E13   SRU       5.430 UNTS.
```